Space-borne cloud and aerosol information for climate research

E. Raschke, GKSS-Research Center

Geesthacht, Germany

1. Introduction

Atmospheric water occurs in all three phases within the atmosphere. It dominates very efficiently the radiative energy transfer and related feedbacks to the atmospheric dynamics, and cascades of processes at the ground. Water vapour is the major atmospheric greenhouse gas, its concentration may react directly to temperature changes at ground levels.

Clouds are in particular affecting the radiative energy transfer within the atmosphere causing an overall reduction of the heating by solar radiation of about 40 Wm^{-2} (15% of the incidenting amount), but trapping also thermal heat radiation within the climate system. They redistribute radiative and condensational heating within the atmosphere (Fig. 1, from Webster and Stephens, 1984). Aerosols mainly „cool" the climate system by about 2 Wm^{-2} or less, but within their thicker layers, as to be observed after strong volcanic emissions, their absorption of solar radiation causes some increase of the temperature.

Aerosols are of both, natural and anthropogenic origin. They may considerably alter the composition and structure of cloud fields, and consequently their radiative transfer properties.

Clouds are sources of the precipitation in most forms. They are locus of intensive chemical reactions (e.g.: Lelieveld and Crutzen, 1991) and modulate also the electric field within the atmosphere. Their occurrence and many other properties are expressions of dynamical processes within the atmosphere and of interactions with the ground by heat and momentum fluxes; in summary, they dominate many climate processes.

It, therefore, is a prerequisite of weather and climate research to measure globally as many as possible properties of cloud fields and also to reproduce them accurately in weather and climate models for scenarios describing the present climate. These validated models should then produce more reliable future climate scenarios.

These statements have many times been documented to establish related institutional, national and international research and operational programmes. Amongst them are such as the JACCS (Japanese Climate and Cloud Study; Asano, 1995 private communications), the ISCCP (International Satellite Cloud Climatology Project; Rossow and Schiffer 1985) and others, which are now coordinated within the Global Energy and Water Cycle Experiment (GEWEX; WMO, 1990) and described in detail in the GEWEX home page (http://www.cais.com/gewex/gewex.html).

This paper reports briefly about the present status of passive space-borne cloud and aerosol observations and explains the need for additional active measurements with cloud profiling radar (CPR) and lidar.

2. Cloud and aerosol properties to be observed within a grid cell

Modern global climate models provide horizontal resolutions of the order of 200 km and in the vertical about 500 m (in the lowest atmosphere) to 1 to 2 km further up. In the near future even higher resolutions might be possible. Such detail should also be approached by global observational systems or in the analyses of coarser measured data. Possibly, only the passive imaging and sounding satellite-borne data will in the horizontal directions reach such detail, or may in some cases even illustrate much finer subgrid-scale detail.

The following quantities should in three-dimensional detail be observed to characterize the radiative transfer properties and latent heat content and structure of cloud fields:

- fractional cover
- vertical extent or thickness
- altitudinal range
- mutual overlap of multiple layers
- particle concentrations in each layer, determining liquid and ice water contents
- particle size distributions in each layer
- particle shape and phase, and ideally also orientation of nonspherical particles
- horizontal structures of these characteristics within a grid cell

All these observations should also be available with high temporal detail of the order of about 3 hours (e.g.: Preuß et al., 1984) to cover the steady effects of atmospheric dynamics on the cloud field properties. But at present only such information will be available with less detail, than desired.

A study group for the GCOS (Global Climate Observing System, GCOS, 1995) summarized in the Table 1 what might be possible in present and in near-future operational systems. Some of the above-mentioned parameters, such as the particle properties, cannot directly be measured from space , but may be estimated only. However, direct measurements, as made in the projects JACCS, FIRE or EUCREX, can provide „typical" ranges.

The present status of interpretations of passive imaging and sounding data is illustrated in the recent results of the ISCCP. Such data cannot provide the detail mentioned above. In particular the estimate of lower cloud boundaries, of internal structures and of the mutual overlap of diffeent cloud sheets can almost not be obtained with the required detail. For instance an error in the lower cloud altitude by about ± 250 m would lead to an error in their temperature of about ± 2K, which would correspond to errors in the downward longwave radiation by about 15 Wm^{-2} and 8 Wm^{-2} at T= 283 K and T= 243 K, respectively.

Estimates of typical particle sizes should better be interpreted as such of an size index, containing also effects of the cloud thickness and fractional cover within the field of view. Within clouds, the particle size distributions show often typical altitudinal variations. An example is shown in Fig. 2.

Higher accuracies may only be achieved by more sophisticated analysis techniques, such as recently developed by Kornblueh (1995, private communication), where satellite data are assimilated into an adjoint version of an one-dimensional boundary layer model, which is nested into the globally analysed meteorological fields.

In summary: the present passive measurements do not provide informations on the internal structure of cloud fields, on their lower boundaries, multiple layers and on thin aerosol layers. However, the data of spaceborne lidar and radar will shed much more light on this part of our complex nature, as it has been demonstrated with ground-based and airborne measurements and from the shuttle as well.

3. Present and near-future space-borne observational systems

Technical and monetary constraints led to the present systems of operational and research-oriented satellites, carrying only passive multispectral imaging and sounding systems. About 4 to 5 geostationary satellites of 3 space agencies provide images (mostly in 2 - visible and infrared windows - and more - atmospheric water vapour and others) with spatial resolutions of about 1 to 4 km and time spacing from 30 to 60 min. Additional polar orbiters of the American NOAA-series carry multispectral imagers (with about 1 km resolution), and several sounders (both: microwave and infrared) to measure the emission of thermal radiation arising from different layers of the atmosphere and containing also very useful information on cloud layers.

These polar orbiters are accompanied by a fleet of international research satellites with more exploratory missions. They carry other sounders - like the SAGE II for horizontal occultation measurements - or multispectral radiometers for the minor but very important gaseous components of the atmosphere and provide additional information on clouds.

These are all passive measurements of reflected or scattered solar and emitted infrared radiation, which in many cases are perturbed by reflections or emissions, respectively, from lower cloud fields or underlying surfaces. A complete description of these present and of most earlier and future satellite systems is provided by the Commission on Earth Observing Satellites (CEOS, 1995).

Other instruments, like the Synthetic Aperture Radars onboard the European satellites ERS-1 and ERS-2 avoid carefully cloud effects on observed surface characteristics. The new satellites of the ADEOS-series will also carry a multispetral radiometer (POLDER) measuring even the polarization of backscattered solar radiation.

The above-mentioned passive multispectral measurements of reflected solar and emitted (transmitted) thermal radiation do not meet these „ideal“ requirements. They contain only limited information on the height, since they are often mixed by information from layers underneath the top-most cloud layers.

There are further uncertainties: e.g.thin clouds are often not seen, or of thicker clouds the satellite observes only their topmost cloud layers. Ground signals, such as the high reflectance from deserts or snow/ice surfaces may often dominate the observed signals, although the multispectral analysis schemes can enhance often spurious cloud and aerosol signals. The ISCCP adds additional information on the status of the ground and atmosphere to improve the cloud identification.

4. Requirements for active probing (Lidar and CPR)

In the more recent discussions and preparations for future exploratory (and later essentially operational) missions several active systems are considered, which make use of short-wave cloud radar (around about 3 to 8 mm) or lidar techniques. These are expected to observe a vertical resolution along the ray-path of about 200 to 500 m which would correspond to uncertainties in their temperature of 1.5 to 3 K. Thus they will approximately meet the above-mentioned required vertical resolutions, which also would fulfil the accuracy requirement for the longwave radiation at the earth’s surface. Such techniques are provided by millimeter radar and the optical or infrared lidar.

Furthermore such a cloud radar, as already shown by various airborne campaigns and also from at least as many ground-based, but directed vertical upward looking measurements, provides much inside into internal cloud field structures, which are in the optical wavelengths often not seen. Its backscattered radiances allow for identifications of cloud particle concentrations and of cloud water contents. At longer wavelengths precipitating areas might much more accurately be identified from space than with a combination of passive microwave radiometers with active rain radar only (see mission TRMM).

Several international workshop had already been organised to prepare the use of short-wave radar techniques in space (see e.g.: ICSU-WMO 1994). The European Space Agency (ESA) is already planning for an „Earth Radiation Mission“ within a sequence of exploratory missions. It will combine passive radiation budget and cloud imaging measurements with those of a lidar and cloud radar.

A space-borne lidar, even only with the simplest backscattering mode, will provide us additional information missed by the others on the

• mostly thinner aerosol layers, often even below thinner cloud or cloud holes

• thin cloud/layers on top of others (as demonstrated by the LITE data).

However, several studies, which form the foundations for the ongoing preparations for space-borne missions, have shown that such active instruments may, for technical reasons, not be able to measure imaging information which provides a spatial resolution and coverage which is similar to those of all passive instruments, e.g. of the AVHRR on the NOAA satellites. Rather, both the radar and a lidar collect their data within limited portions of the field of view of the satellite, which is available from polar orbiter altitudes (600 to 800 km).

Their match with concurrent imaging data, however, will considerably improve our present knowledge on the atmospheric aerosol and cloud fields. Much other detailed observations are required to validate the results derived from such space-borne measurements. They might be done during the next decades with highest intensity within the at present five GEWEX Regional Experiments, of which one is the GEWEX Asian Monsoon Experiment (GAME) coordinated by Japanese authorities.

5. A few conclusions

In summary, we conclude, that passive remote measurements of clouds and aerosols from space can provide only limited information on their characteristics. In particular their internal structures and multiple layers and lower boundaries, as well, are not observed. Only active sounders, measuring in the solar and infrared (lidar) and millimeter regions (cloud profiling radar) can significantly contribute to an improved measurement of such information. When jointly used they allow measurements in the wide range of optical thickness provided from thin aerosol layers (see measurements during the shuttle experiment LITE) to thick cumulus towers.

Despite of all enthusiasms for new engineering hardware, one should never overlook the urgent need for new and very intelligent analysis techniques, which make use if these and other informations. Such research must be an integral part of any instrumental programme.

6. References

CEOS, 1995: Co-ordination for the next decade. 1995 CEOS Yearbook, available from the CEOS secretariats at NASA/NOAA, ESA and STA/NASDA.

GCOS, 1995: Global Climate Observing System - Plan for Space-Based Observations, WMO/TD - No. 684, available from World Meteorological Organization in Geneva.

ICSU-WMO, 1994: Utility and Feasibility of a Cloud Profiling Radar (GEWEX Topical Workshop in Pasadena, Calif.), IGPO-Publication Series, Nr. 10

Lelieveld J. and P.J. Crutzen, 1991: The Role of Clouds in Tropospheric Chemistry. *Journ. Atmosph. Chemistry*, 12, 229-267

Preuß, H.J., E.Raschke, M. Daniel, 1984: Studies of the Sampling of Space-borne Radiation Budget Measurements, *Meteor. Rundschau*, 37, 52 - 64.

Rossow, W. B. and R. A. Schiffer, 1991: ISCCP cloud data products. Bull. American Meteorol. Soc., 72, 1-20.

WMO, 1990: Scientific Plan for the Global Energy and Water Cycle Experiment (GEWEX). WMO/TD - No. 376, WCRP-40, 83 pp

	Horizontal Resolution (km)	Temporal resolution	Accuracy (RMS error)	Notes
Cloud fractional cover	100	3 h	10 %	
Cloud top height	100	3 h	0.5 km	(1)
Cloud base height	100	3 h	0.5 km	(1)
Total liquid water content	100	3 h	20 %	
TOA net shortwave radiation	100	3 h	5 W/m^2	(2)
TOA net longwave radiation	100	3 h	5 W/m^2	(2)
Multi-purpose IR/VIS imagery	5	30 min.	-	(3)

Notes:

(1) Accuracy higher in planetary boundary layer;

(2) Required principally for model validation, not time critical;

(3) Required to assist real-time observation monitoring and analysis/forecast validation.

Table 1: Observational requirements for cloud and radiation fields as envisaged for the Global Climate Observing System (GCOS, 1995)

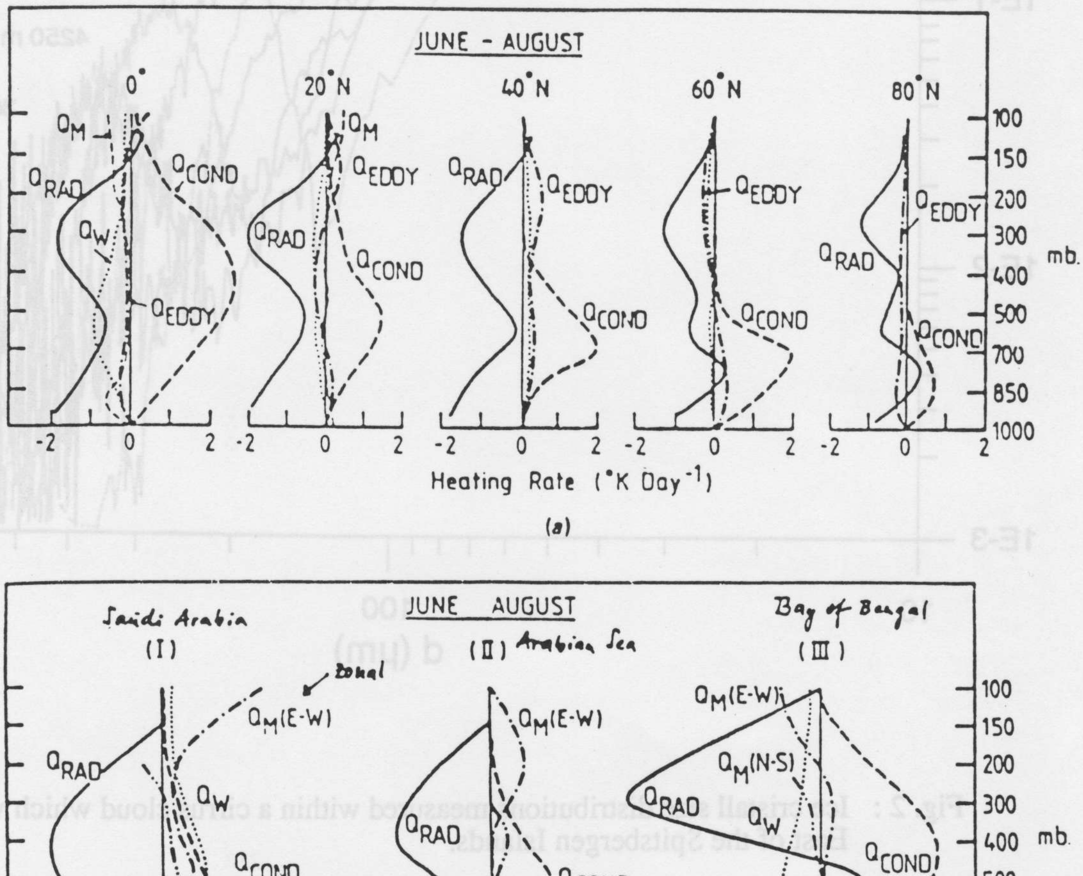


Fig. 1 : Vertical heating rates due to radiation (RAD), condensation (CON), mean and eddy heat convergence (M, EDDY) and adiabatic motions (W). (N-S) and E-W) describe longitudinal and latitudinal fluxes. These estimates are published by Webster and Stephens (1984, in „The Global Climate", ed. J.T. Houghton, Cambridge Univ. Press)

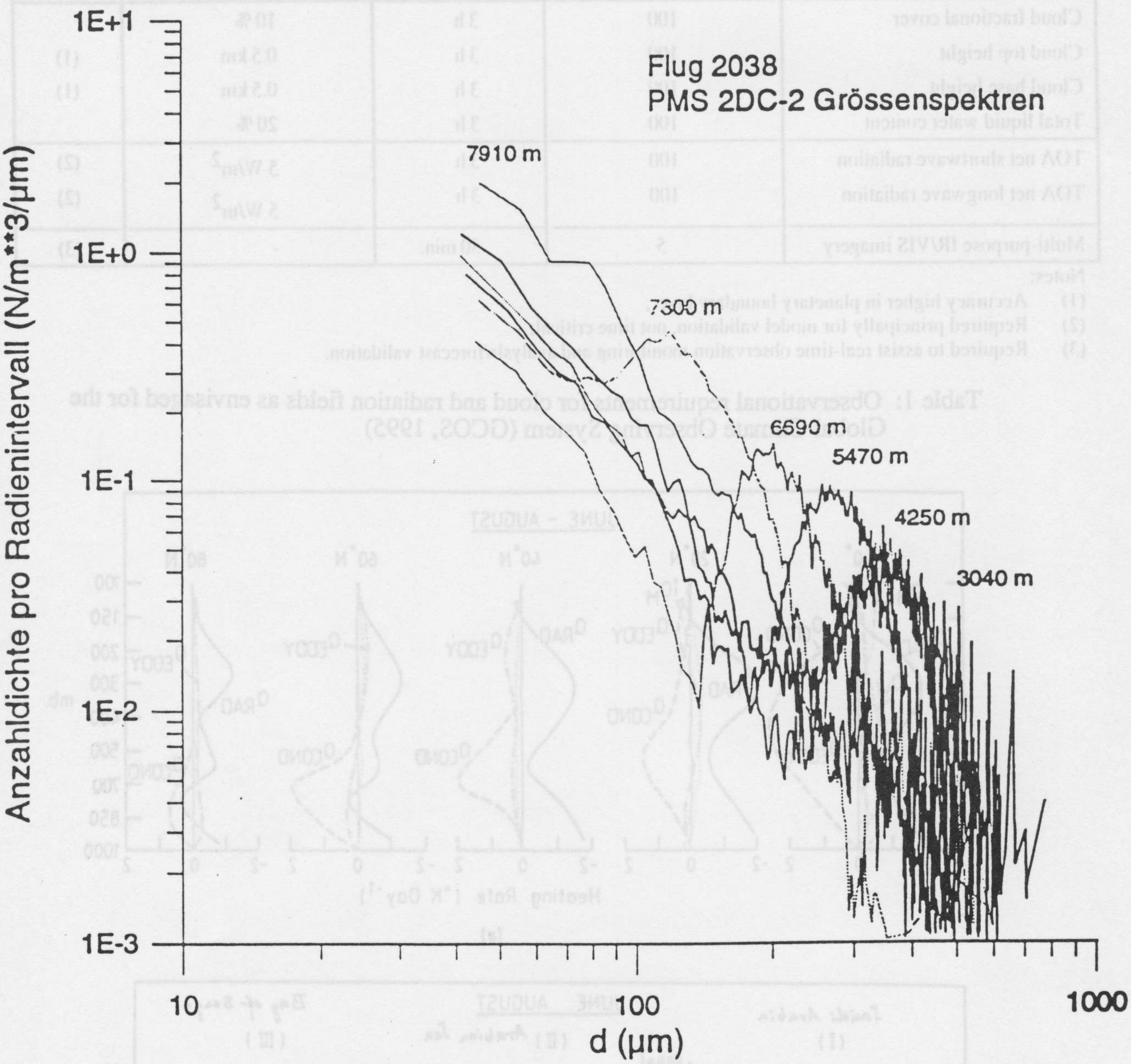


Fig. 2 : Ice cristall size distributions measured within a cirrus cloud which was located East of the Spitsbergen Islands.

Space-borne Cloud and Aerosol Information for Climate Research

E. Raschke, GKSS Research Center
D-21502 Geesthacht, Germany
raschke @ gkss. de

1. **Rôle of aerosols and clouds on energy and water transfer in the climate system**

2. **Which information should be provided by observational systems ?**

3. **Present space-borne observations: solar, terrestrial (ir, mw)**

4. **Requirements for active probing - project proposals**

5. **A few conslusions for space-borne systems**

Nara 1995

1. Rôle of aerosols and clouds on energy and water transfer in the climate system

(a) Aerosols and Clouds alter the radiation budget

- aerosols : generally "cool" (~< 2 Wm^{-2})
- all cloud fields : generally "cool" (~ 20 Wm^{-2})
  but some may "warm"

(b) They redistribute radiative and condensational heating / cooling within the atmosphere

(c) Aerosols alter radiative transfer characteristics of clouds
precip. , smaller particles, chemistry (O_3 ; NO_x , CO)

(d) Clouds transport water (and latent heat)

(e) Clouds produce precipitation (rain / snow)

Nara 1995

2. Which information should be provided by observational systems on aerosol and cloud layers within a grid cell ?

(1) Radiative transfer properties of a field (within a grid area)

(a) fractional coverage

(b) vertical extent (3-d) / multiple layers

(c) altitudinal range

(d) particle concentrations/total volume contents –> IWC/LWC

(e) particle size distributions

(f) particle shapes

(g) horizontal structures of these quantities (b) through (f)

(h) particle phase (snow/ice) - a shape factor ?

(2) Time variability of all quantities mentioned above

(a) amount

(b) density

(c) particle / drop size distributions

Nara 1995

3. Present space-borne observational systems - related projects

The ISCCP and the NASA/NOAA pathfinder programmes - as the major operational cloud and aerosol analysis projects - make use of passive imaging and sounding data from

- polar orbiting satellites : NOAA - AVHRR and TOVS
- geostationary satellites : imaging - solar, ~ 6 μm, ~ 11 μm,
- military satellites : DMSP - SMM/I (various versions)

There are also other satellites

- now : ERS-1 and -2 (ATSR), Meteor 3, ...
- in future : ADEOS (with POLDER)

- see CEOS, 1995 -

Nara 1995

4. Requirements for active probing - project proposals

More accurate knowledge is required on

1	• cloud boundary altitudes (± 200 m —> ± 1.2 K)	CPR, L
4	• cloud top morphology	CPR, L
2	• multiple cloud layers (thin on top of others)	CPR, L
3	• internal structure, LWC and IWC	CPR
1	• aerosol (and pre-condensation phase) layers between cloud field elements	L
2	• aerosol layers on top the planetary boundary layer	L
3	• low level fog	L

CPR = cloud profiling radar (~3 to 8 mm)

L = lidar

Nara 1995

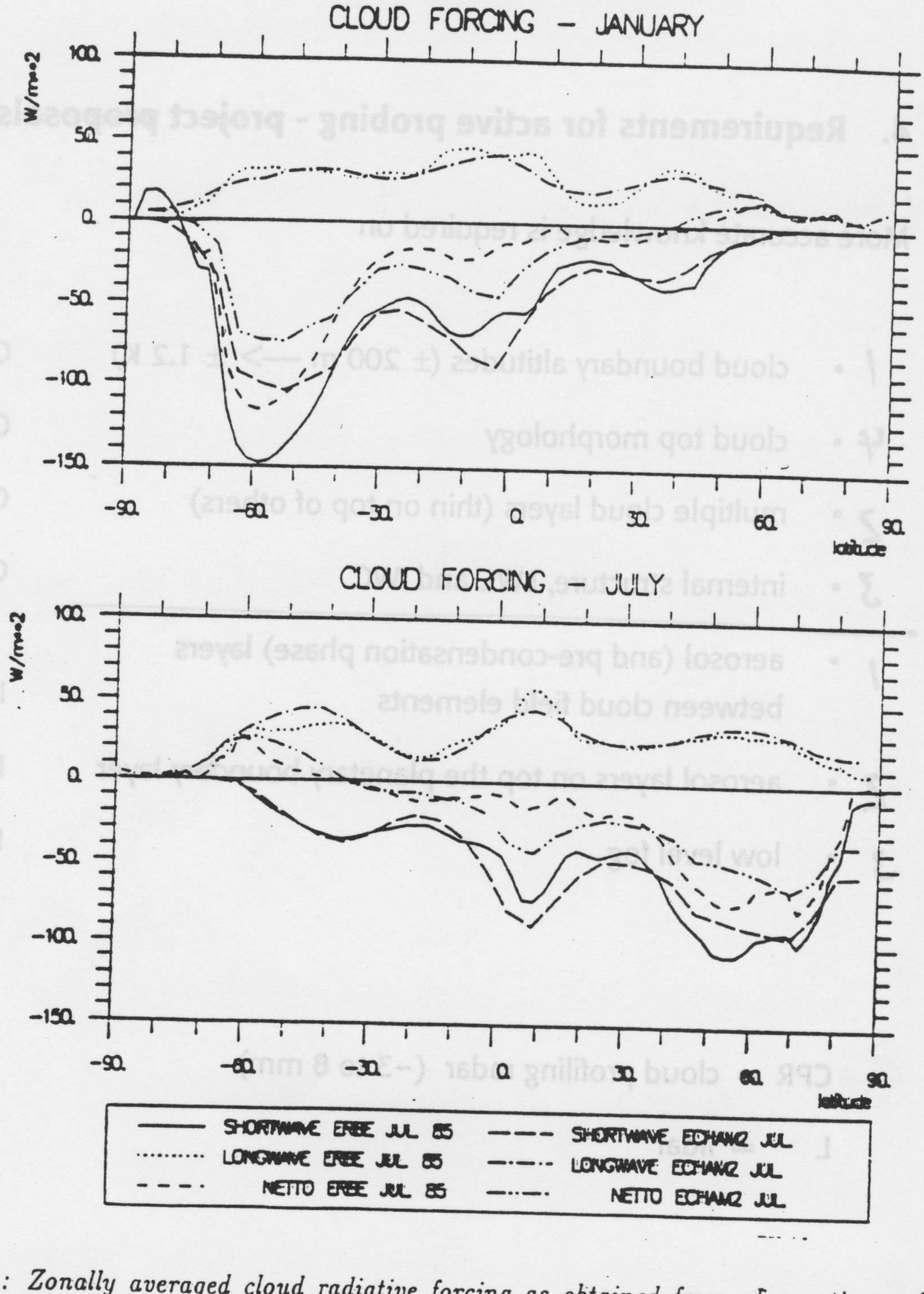
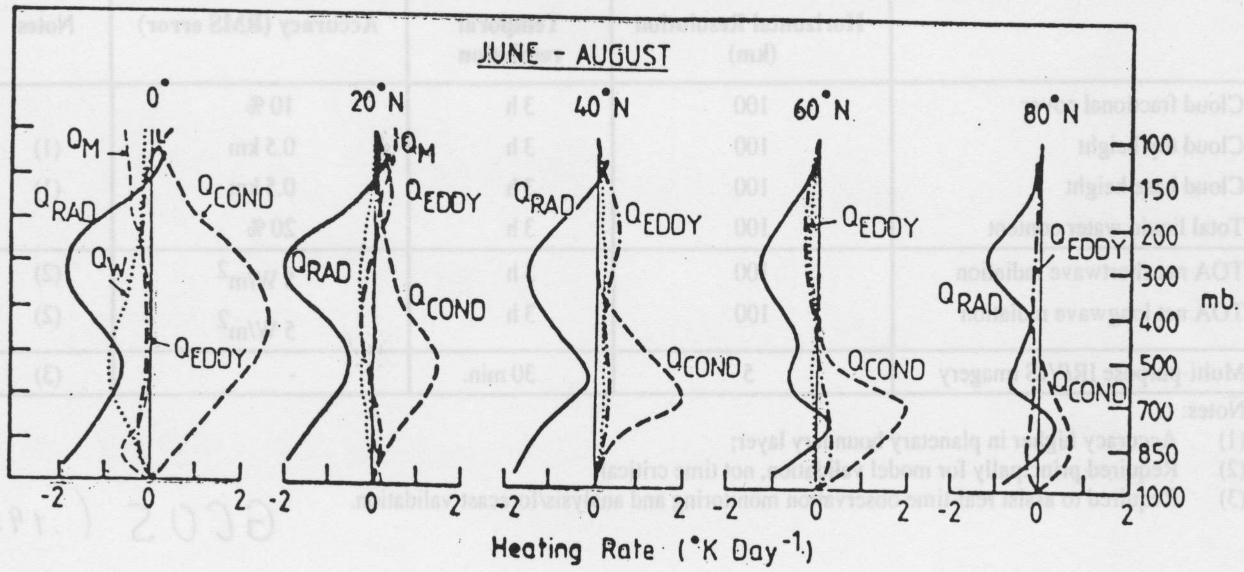
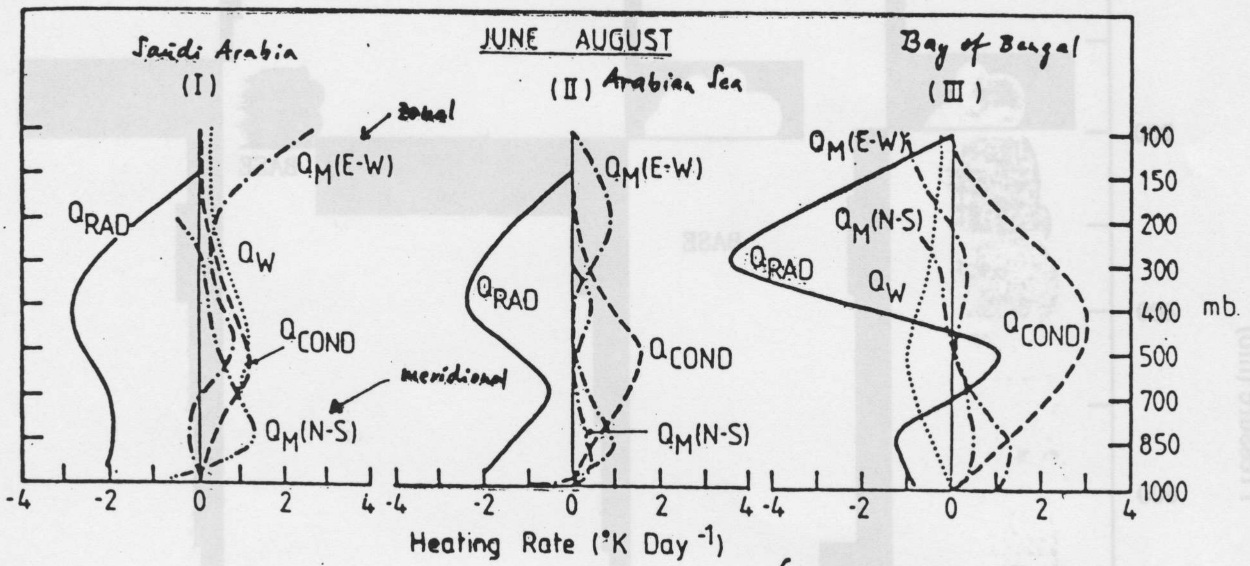


Figure 3.1: *Zonally averaged cloud radiative forcing as obtained from observations of the Earth Radiation Budget Experiment for January 1986 and July 1985 and as simulated by the climate model ECHAM 2 in a 20-year climate experiment (from Roeckner et al., 1991).*

ZONAL AVERAGES



(a)



(b)

(Webster, 1981)

Webster and Stephens, 1984

RAD = radiation

COND = condensation

M = mean heat convergence

EDDY = eddy " "

W = adiabatic motions

Table IV-3: Other two-dimensional fields

	Horizontal Resolution (km)	Temporal resolution	Accuracy (RMS error)	Notes
Cloud fractional cover	100	3 h	10 %	
Cloud top height	100	3 h	0.5 km	(1)
Cloud base height	100	3 h	0.5 km	(1)
Total liquid water content	100	3 h	20 %	
TOA net shortwave radiation	100	3 h	5 W/m^2	(2)
TOA net longwave radiation	100	3 h	5 W/m^2	(2)
Multi-purpose IR/VIS imagery	5	30 min.	-	(3)

Notes:

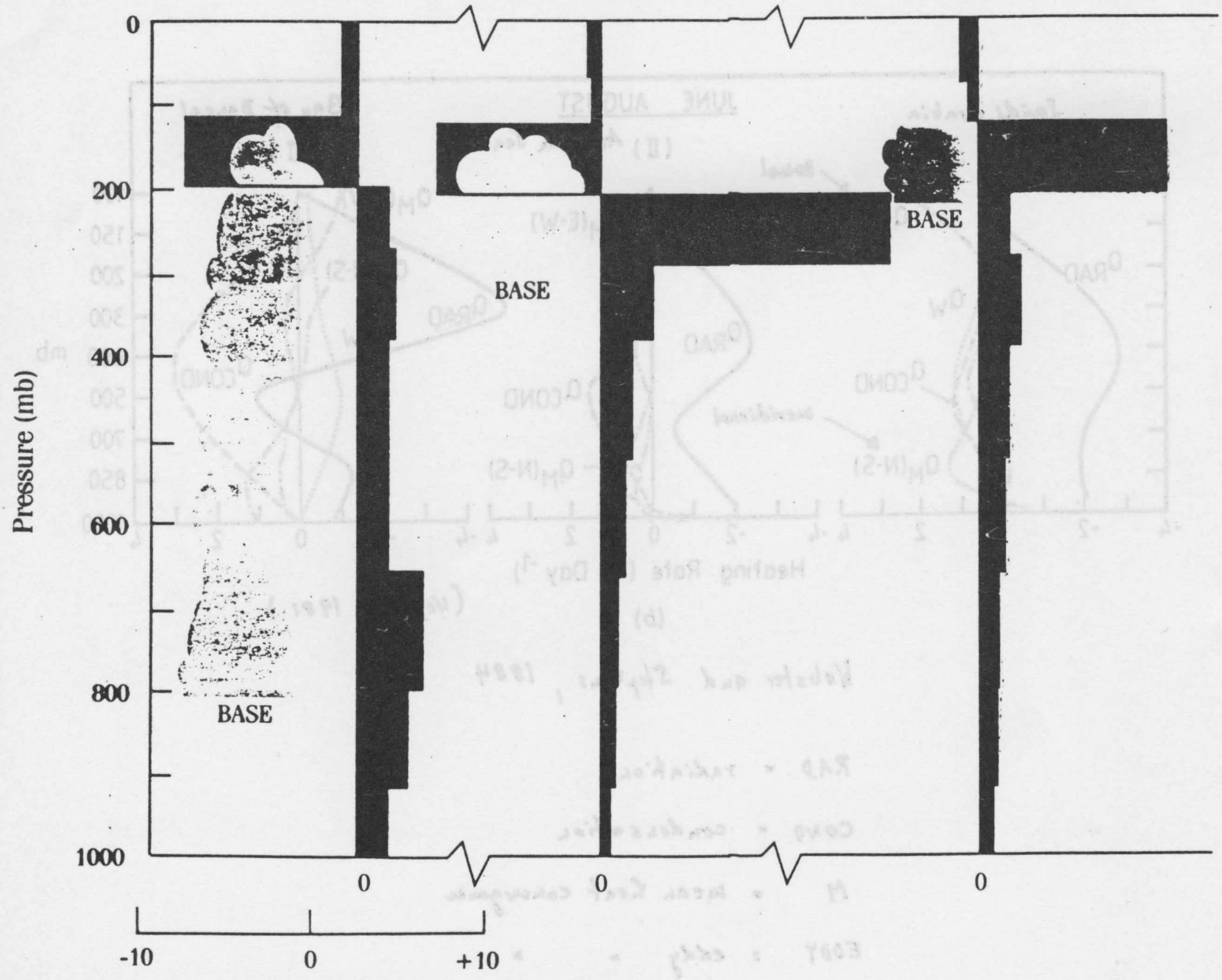
(1) Accuracy higher in planetary boundary layer;

(2) Required principally for model validation, not time critical;

(3) Required to assist real-time observation monitoring and analysis/forecast validation.

GCOS (195)

A. Slingo



Infra-red atmospheric forcing due to cloud (K/day)

Clouds with lidar from space

(simulations by Univ. of Munich for ESA)

- water clouds : $\tau > 2$ single shot
- ice " : $\tau = 1$ " } day
  - $\tau = 0.25$ 25 shots }
  - $\tau = 0.2$ single shot } night
  - $\tau = 0.05$ 25 shots }
- multiple scattering allows to 'see' low stratus below cirrus (τ : 1.5 to 4)
- aerosols : 100 shots for dense layers
  - no s. a. of background aerosol
- ISCCP - requirements can be met with averages over 2° fields (~ 200 km

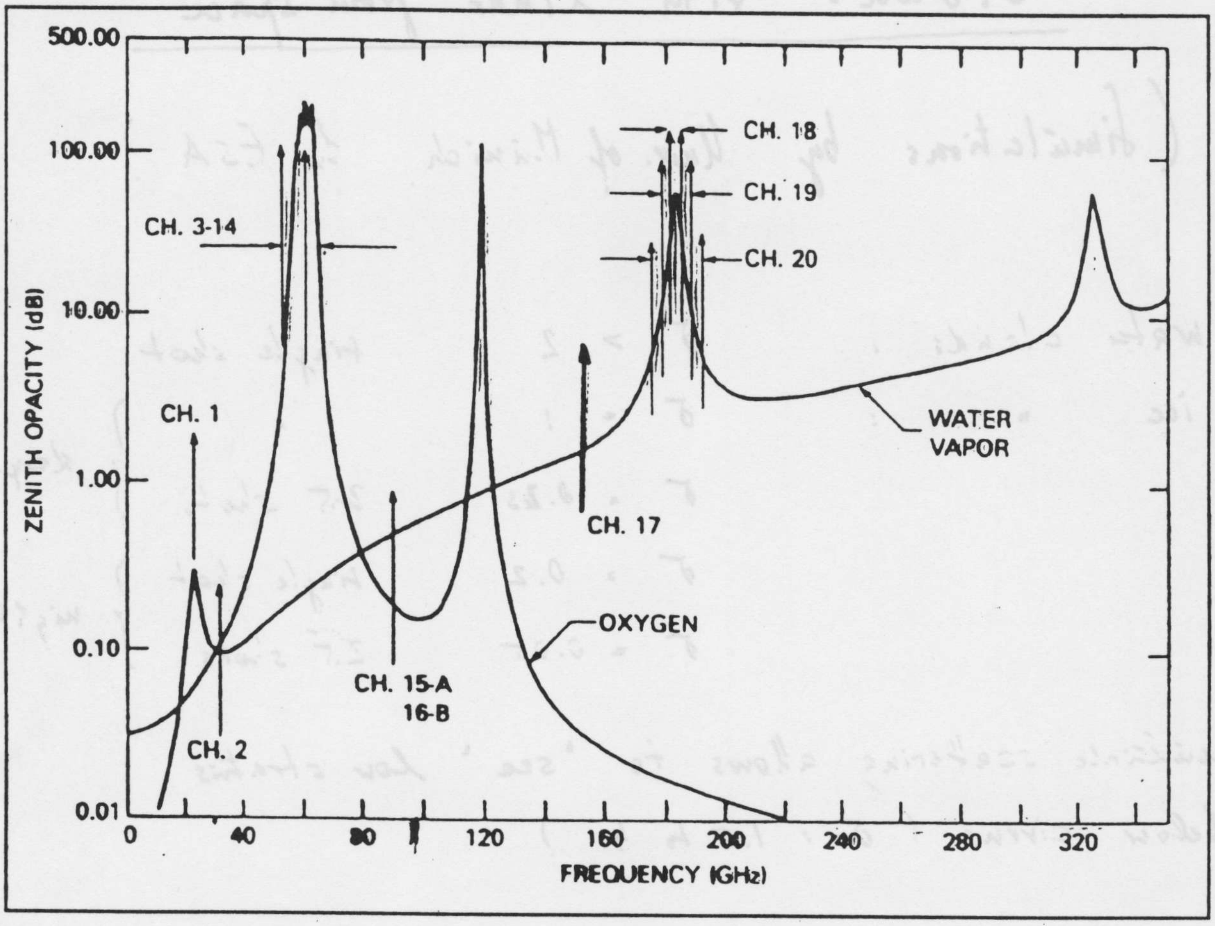


Figure 1: **Atmospheric attenuation at microwave frequencies due to oxygen and water vapour molecules, together with the AMSU (A and B) channel positions.**

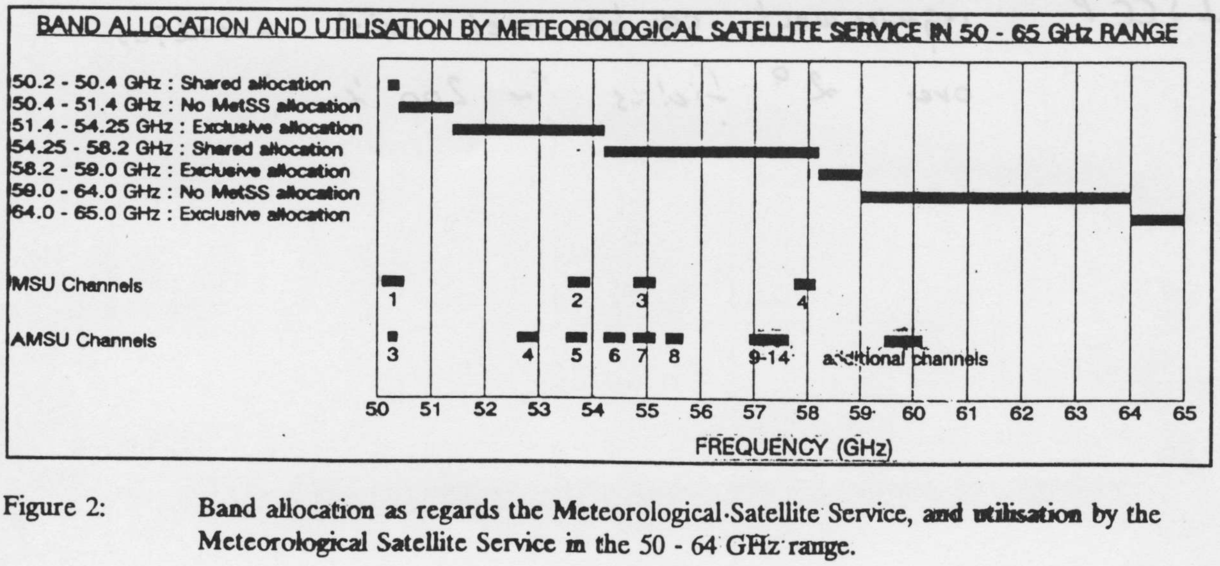
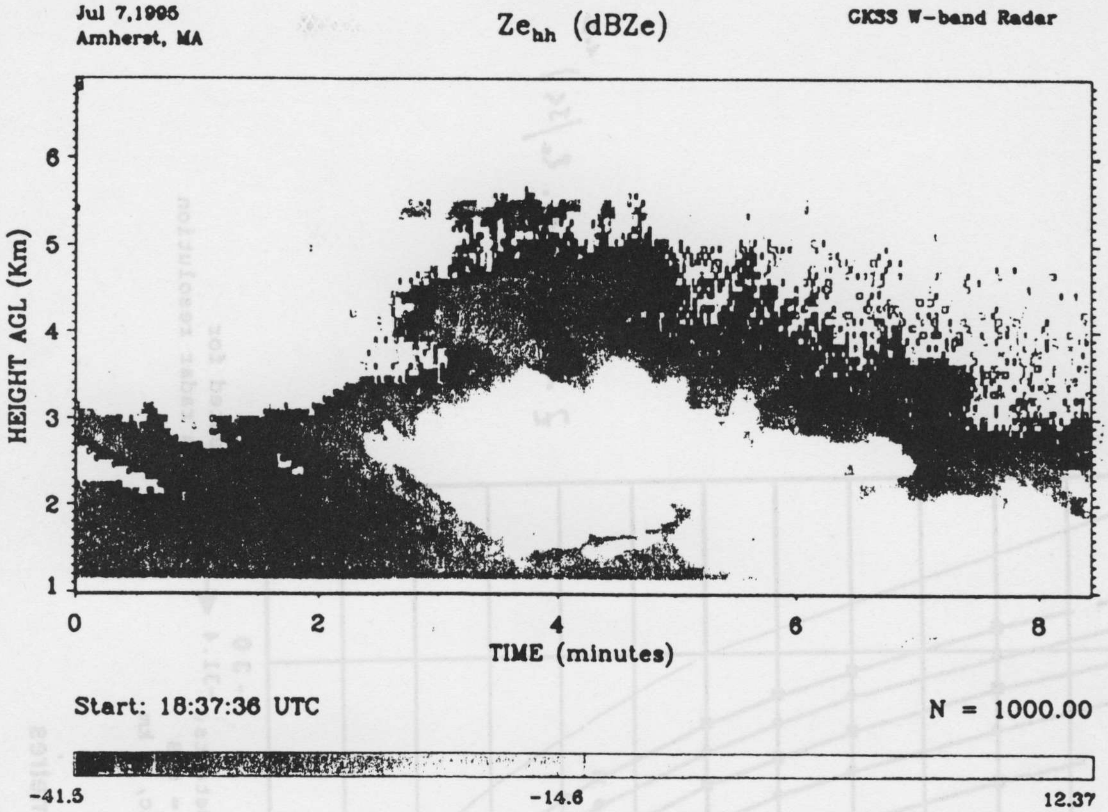
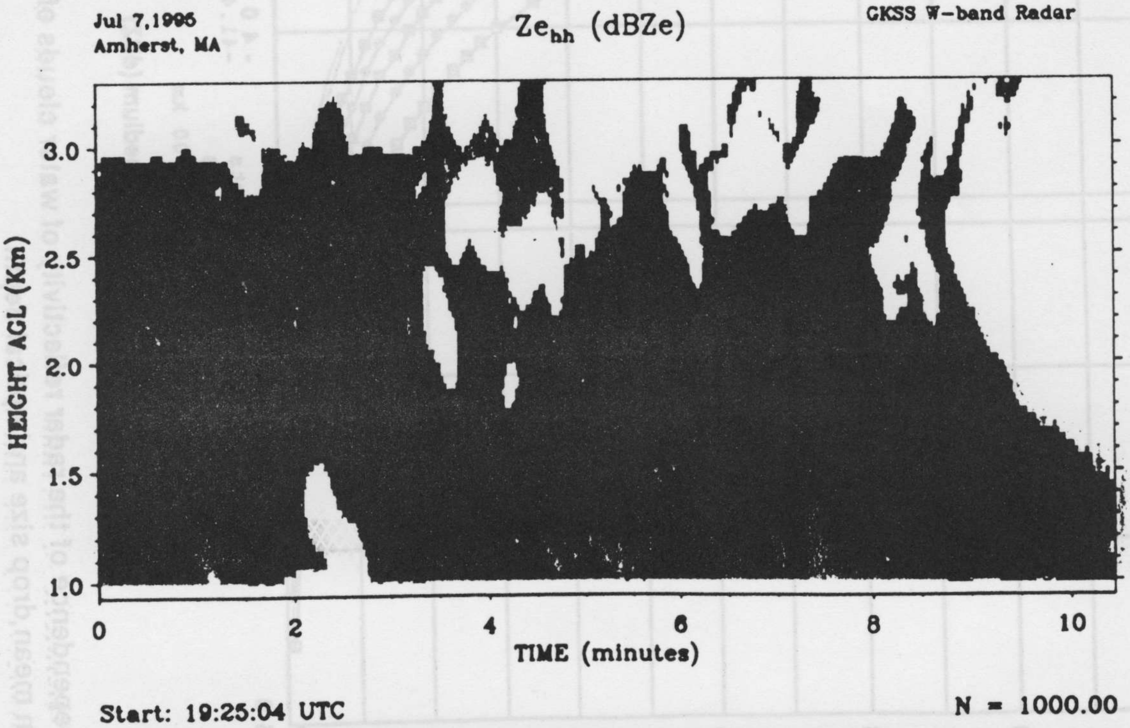


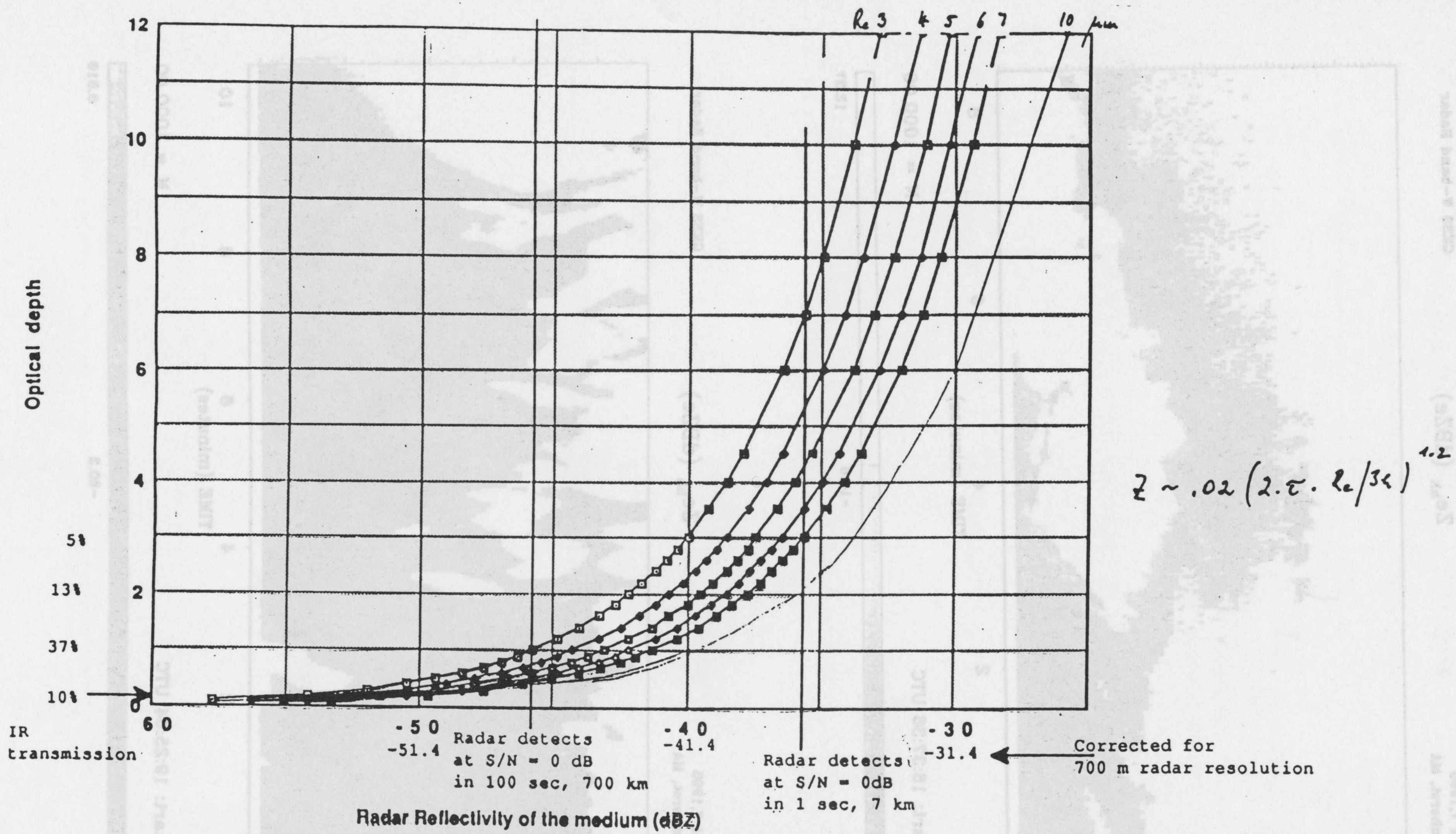
Figure 2: **Band allocation as regards the Meteorological Satellite Service, and utilisation by the Meteorological Satellite Service in the 50 - 64 GHz range.**



Jul 7,1996
Amherst, MA
Ze_{hh} (dBZe)
GKSS W-band Radar
HEIGHT AGL (Km)
TIME (minutes)
Start: 18:37:36 UTC
N = 1000.00
-41.5
-14.6
12.37



Jul 7,1996
Amherst, MA
Ze_{hh} (dBZe)
GKSS W-band Radar
HEIGHT AGL (Km)
TIME (minutes)
Start: 19:25:04 UTC
N = 1000.00
-41.5
-20.3
0.819



Dependence of the radar reflectivity of water clouds of depth 500 metres on mean drop size and optical depth

International Cirrus Experiment   Mission ICE 215

8500 m

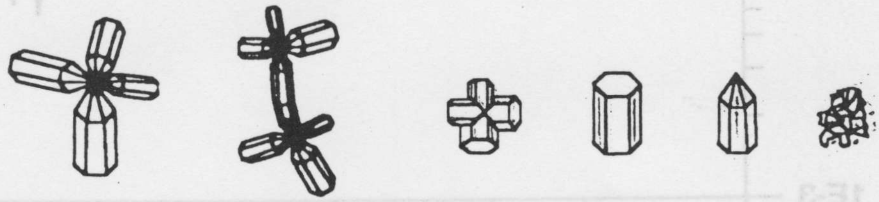
Cloud top

8200 m

temperature: **-39 ° C**
particle size: **maximum 230 µm / mean 110 µm**
air: **saturated relative to water / supersaturated relativ to ice**
number concentration: **28 l^{-1}**

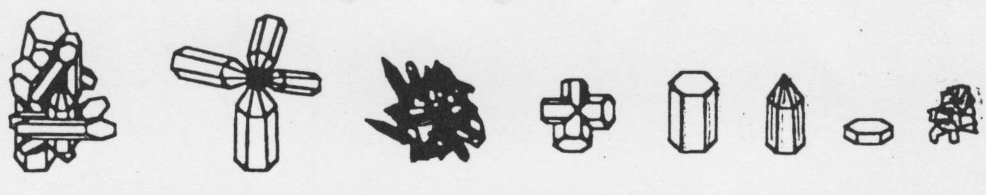
7600 m

temperature: **-34 ° C**
particle size: **maximum 1240 µm / mean 180 µm**
air: **not saturated relative to water / supersaturated relativ to ice**
number concentration: **28 l^{-1}**



7000 m

temperature: **-26 ° C**
particle size: **maximum 1140 µm / mean 125 µm**
air: **saturated relative to water / supersaturated relative to ice**
number concentration: **360 l^{-1}**



5000 m

Cloud base

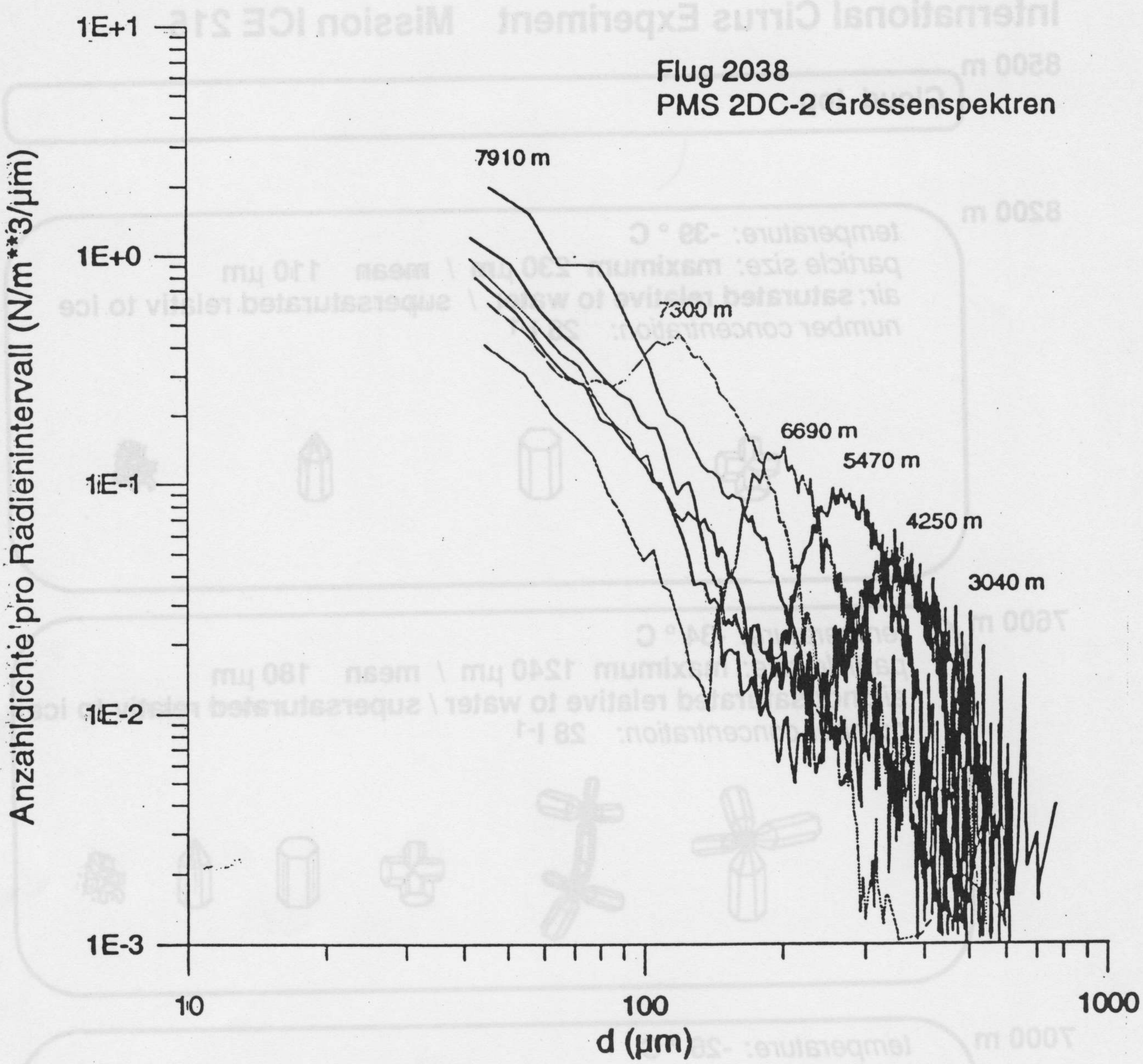


Abbildung 16: Ausgewählte Grössenspektren für Flug 2038. d bezeichnet den Durchmesser einer Sphäre gleicher Querschnittsfläche.

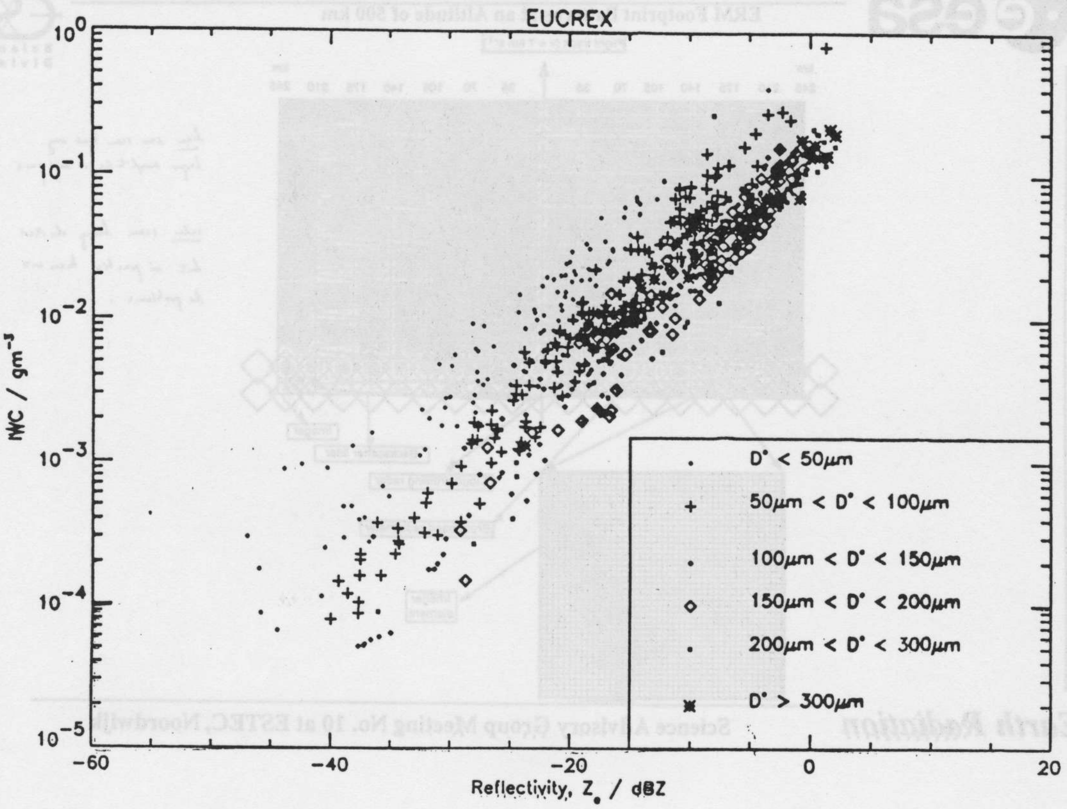
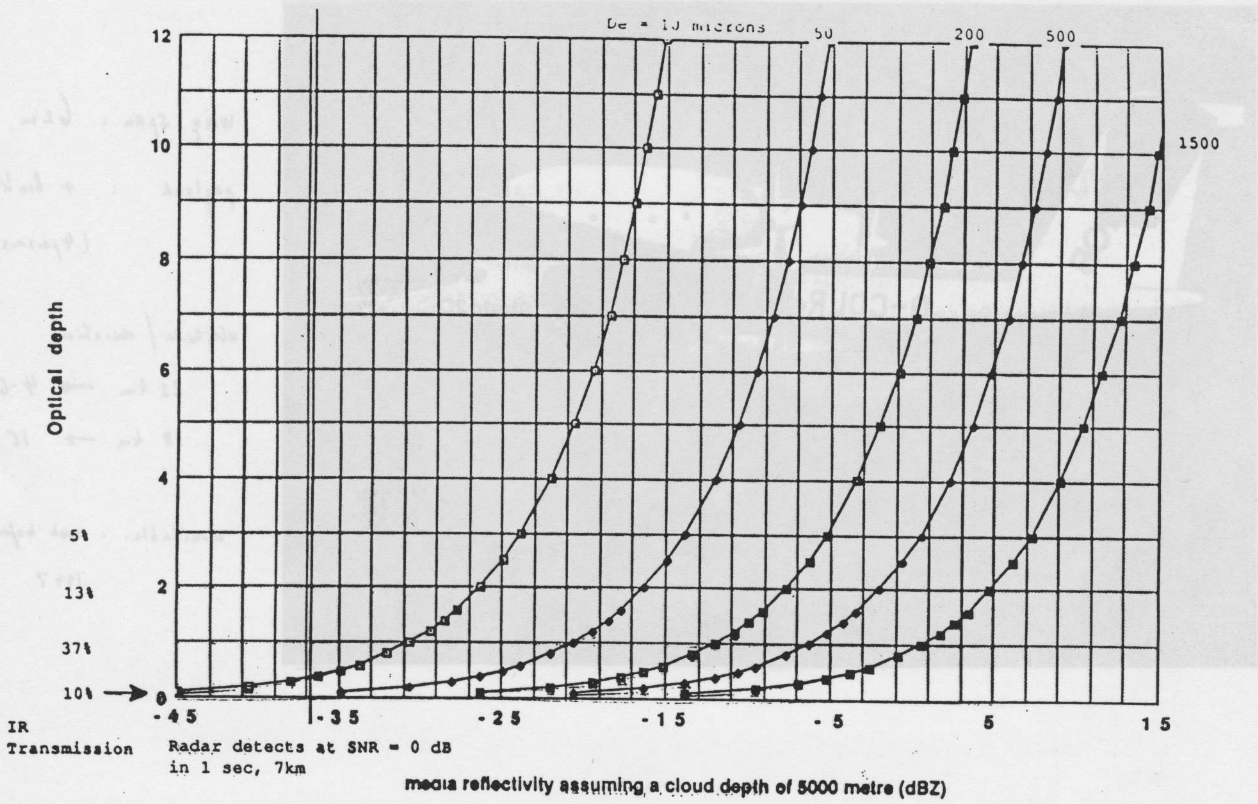


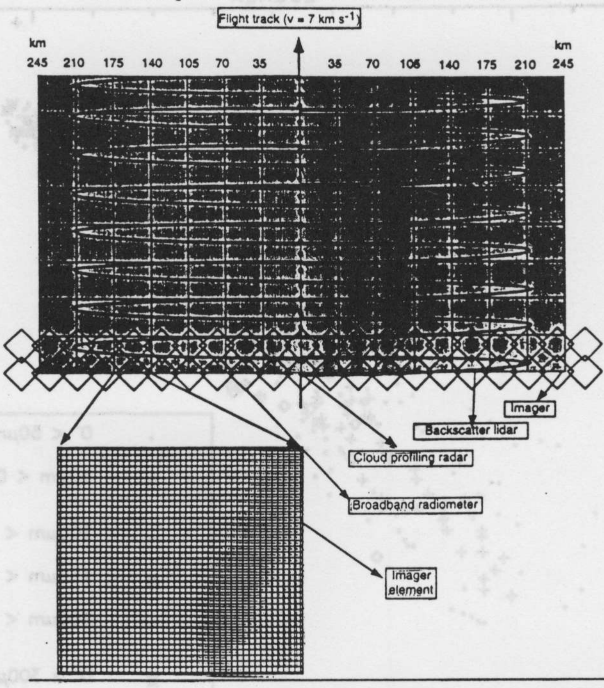
Figure 7 a)



Dependence of radar reflectivity of ice clouds on IR optical depth and mean drop size

esa

ERM Footprint Patterns at an Altitude of 500 km



lidar can scan but very larger amplitude is not good

radar scan being checked but in practice there will be problems.

Earth Radiation Science Advisory Group Meeting No. 10 at ESTEC, Noordwijk

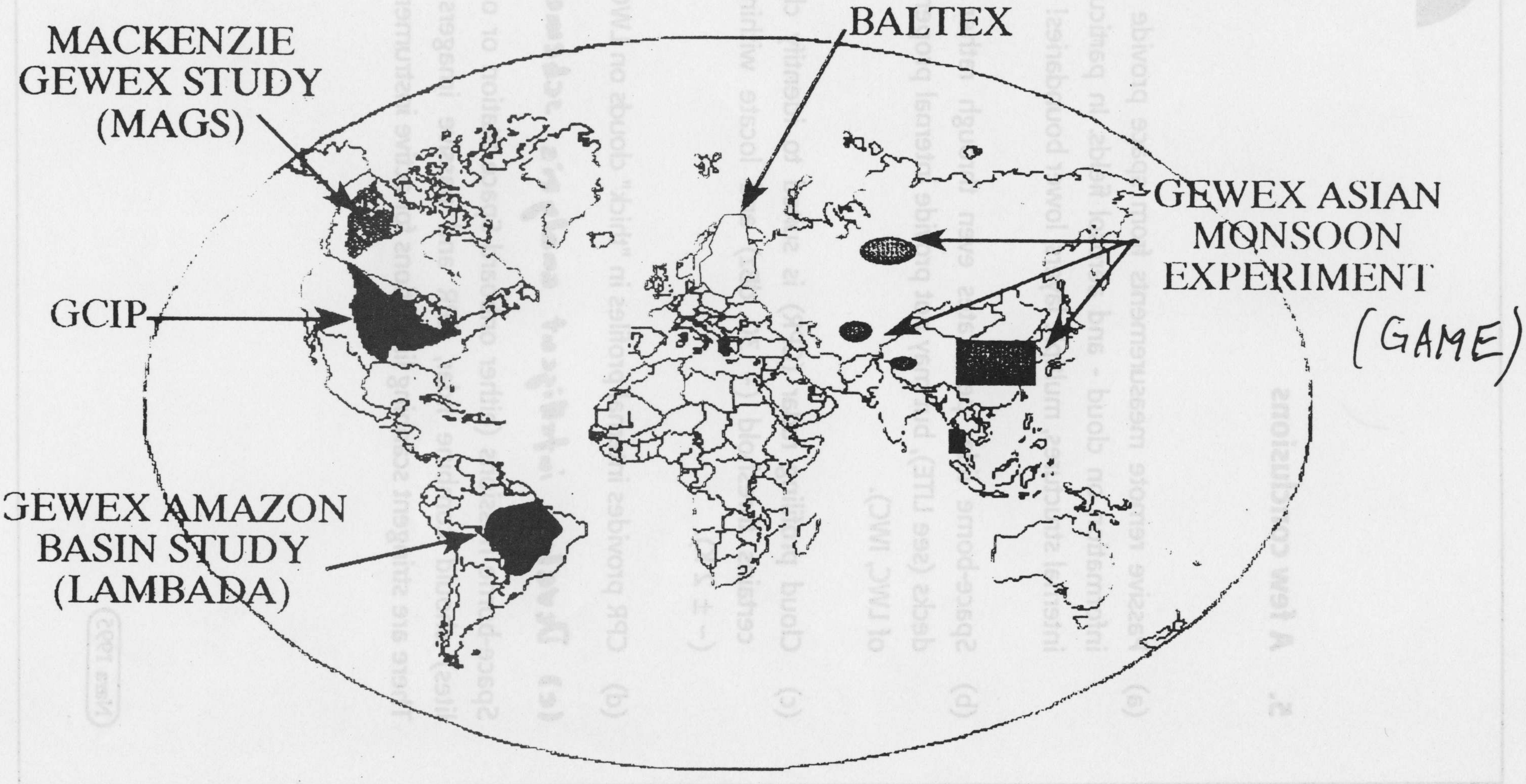
wing span : 62 m

payload : + 800 kg (4 persons)

altitude / duration :
22 km → 4-6 h
18 km → 15 h

available : not before 1997

REGIONAL GEWEX CONTINENTAL-SCALE PROJECTS



5. A few conclusions

(a) Passive remote measurements from space provide only limited information on cloud - and aerosol fields. In particular we miss internal structures, multiple layers, lower boundaries!

(b) Space-borne lidar penetrates even through rather thick cloud decks (see LITE), but may not provide internal properties (profiles of LWC, IWC).

(c) Cloud profiling radar (CPR) is suited to identify clouds above certains threshold (~ 30 dBz) and locate within ± 250 m (~ ± 2 K).

(d) CPR provides internal profiles in "thick" clouds on LWC, IWC.

(e) Develop intelligent analysis schemes.

Space-borne missions (either onboard Space Station or onboard Satellites) should combine lidar, CPR and passive imagers / sounders. There are stringent scanning limitations for active instruments.

Nara 1995